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Far Infrared Imaging Spectrometer for Large Aperture Infrared Telescope System

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This report describes a Far Infrared Imaging Spectrometer for a Large Aperture Infrared Telescope System.

The objective was to develop a technology base to support the Space Based Space Surveillance Program for the identification of cold objects in the earth limb or deep space. The program emphasized also certain basic infrared astrophysics problems related to the kinematics and composition of extended infrared objects, their energetics, and the evolutionary state. The instrument described is a high resolution Fabry-Perot spectrometer (10^3 < Resolution < 10^4) for wavelengths from about 50 to 200 micrometer, employing extended field diffraction limited imaging.

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A FAR INFRARED IMAGING SPECTROMETER

FOR THE LARGE APERTURE INFARED TELESCOPE SYSTEM

Summary

The objective of this program is to develop a technology base to support the Space Based Space Surveillance Program for the identification of cold objects in the earth limb or deep space. The program emphasizes also certain basic infrared astrophysics problems related to the kinematics and composition of extended infrared objects, their energetics, and the evolutionary state. This investigation will use high resolution spectroscopy ($10^3 < R < 10^4$), over the wavelength interval from about 50 to 200 μm coupled with extended field diffraction limited imaging. The program proposes to build a Far Infrared Imaging Spectrometer for a Large Aperture Infrared Telescope System Shuttle Sortie mission to achieve these goals.

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1. Introduction

The objective of the Large Aperture Infrared Telescope System (LAIRTS) is to investigate the effect of the natural infrared celestial background, a mission which affects all future Space Surveillance and Space Defense Systems. LAIRTS will initially carry two experiments: a staring imaging camera between 5 and 25 μm and a scanning Far Infrared Imaging Spectrometer (FIRIS) covering the spectrum between 50 and 200 μm with variable resolving power up to $\lambda/\Delta\lambda \equiv R \backsim 3 \times 10^4$. LAIRTS will be flown on a shuttle sortie mission in 1989 using state of the art cryogenically cooled optics, advanced mosaic and discrete focal plane arrays with multiplex electronics and on-board data processing techniques. This report outlines the scientific and military relevance of LAIRTS and FIRIS and gives a general description of FIRIS and its developmental program for flight and data analysis.

FIRIS provides the opportunity for high sensitivity observations with high spectral and spatial resolution now feasible in the far infrared ($50 < \lambda < 200$ μm). FIRIS consists of two spectral bands: Band 1 (50-100 μm) and Band 2 (100-200 μm) with background limited Noise Equivalent Power (NEP) of $\backsim 1 \times 10^{-17}$ $WHz^{-1/2}$.

2. Military Relevance

LAIRTS will address the critical technologies to support the Space Defense Initiative (SDI). It will identify specifically

advancement in four major areas: long life cryogenic endurance systems, low scatter optics and baffles, fast on-board data processors, and long wavelength infrared focal plane technology. The mission will provide real time target detection against extended sources, high spatial resolution background data to validate celestial, zodiacal and atmospheric models for space surveillance systems and a stellar number density data base for advanced space target missions.

FIRIS will address a number of DoD related issues related to Anti-Satellite (ASAT), Space-Based Space Survelliance (SBSS), and Ballistic Missile Defense (BMD) applications. The basic scenario for these applications is aircraft or space surveillance of targets against the cold space or earth limb background. High resolution spectra at far infrared wavelengths will be used to model typical targets, the celestial background and the upper atmosphere. Far infrared wavelengths are chosen because the molecular composition of exhausts, plumes, dumps and of the atmosphere is more tractable and less confused than in the near infrared bands, usually correspond to colder excitation situations, and because the far infrared is unexploited for SDI systems.

2.1 Target Signatures

Targets of interest are re-entry vehicles, buses, and satellites (including those themselves engaged in surveillance activities) which are not characterized by high energy burns or large aerodynamic heating, i.e. with typical effective skin

temperatures less than 300 K. Objects engaged in passive cooling have effective temperatures which can be less than 100 K on some surfaces. Satellites with on-board cryogenic infrared sensors may have even smaller effective skin temperatures on some surfaces. Detection and identification of such targets at extreme range (> 1000 km) is possible using their (1) thermal emission, (2) exhaust, dump and plume spectra, and (3) spatial characteristics and track.

2.2 Cold Target Skin Emission

For the coldest targets, FIRIS provides a means of obtaining the low resolution (R < 100) spectra of skin emission at maximum sensitivity. As a "cryogenic filter" the spectrometer blocks all emission falling onto the detectors outside of the selected band of interest so that only the cold sky background and detector noise contributes against a warm earth or limb. Thus, detectors with noise equivalent powers NEP <10E-17 w/$\sqrt{\text{Hz}}$ can be employed. Furthermore, out of band emission from STS contaminants (RCS burns, water dumps and vehicle outgassing) is also rejected. The detailed emission spectra of targets at wavelengths greater than 50 μm can be analyzed to determine target skin temperature and to discriminate against confusion from celestial sources, zodiacal emission and contaminating particles carried along with the STS. Since some cold targets may have black body peaks longward of 30 μm, FIRIS will be well suited to determine accurate target characteristics.

2.3 Exhaust, Plume, and Dump Characterization

Identification and characterization of targets from the molecular spectra of their exhausts and dumps is a prime goal of the FIRIS instrument. RCS burns of the STS are typical of the type of activity that can be used to characterize an otherwise non-cooperative target. These "burns" are actually controlled directional venting of propellant gases at relatively low temperatures which (1) quickly spread into large clouds, (2) thermalize to the space environment and often condense out into particulates, and (3) often chemically react with the residual atmosphere. Typical products include H_2O, O_3 and oxides of nitrogen. Other more exotic products such as NH_3 may be produced under unusual situations, and the spectra of some of them will be detectable with the FIRIS with sufficient velocity resolution to measure the thrust vector along the line of sight. The imaging capability obtained from FIRIS allows the morphology of emission plumes to be studied in detail. This information can yield the thrust vector and additional insight concerning the origin of the plume (e.g. venting, RCS, flash evaporator operation).

2.4 Atmospheric Phenomenology

IR absorption by H_2O, O_3, and CO_2 is the major limiting factor in all ground based IR surveillance systems; thermal emission by these absorbers is a major contributor to the background against which they must operate. In the SBSS and ASAT scenarios, the composition of the mesosphere and thermosphere is important while, for some Ballistic Missile Defense (BMD) situations, composition of the upper stratosphere is also important.

To accurately model the effects of molecular absorbers, their (a) altitude distribution, (b) geographical distribution, (c) time scale of variation, and (d) molecular excitation must be determined. Unfortunately, molecular composition in the mesosphere and thermosphere can only be reliably determined using sounding rockets, which only give "snapshot" information at one geographic location and by ground-based spectroscopy that also yields data for one point only. As a result, the distribution of even such important constituents as H_2O and CO is not known in the thermosphere and is only well determined at spot locations in the mesosphere. Furthermore, large spatial and temporal variations in these constituents have been detected but are not well studied and understood.

FIRIS will have a significant impact upon this deficiency by allowing spectroscopic observation of the major IR absorbers in low lying rotational lines (thus unconfused and easily analyzed) by limb-scanning emission spectroscopy. This technique is both the most effective for yielding reliable altitude profiles and also allows very small trace amounts of absorbers to be detected so that collateral geophysical information concerning the upper atmosphere can also be obtained.

Another important potentially confusing factor in the IR background is the variable presence of particulates in thin layers often near the poles (e.g. the polar scattering layer). FIRIS will have significant impact on the understanding of these phenomena by observing the layering and variation of constituents that can condense into particles. By observing the intensity

ratio of lines of well-mixed species, we can also determine the physical temperature in thin mesospheric and thermospheric layers.

Rapid variations in composition and physical state generate a flickering background to IR sensors and negate image comparison algorithms. FIRIS can choose to look against optically thick H_2O lines which do not flicker. The enormously high sensitivity of FIRIS in limb-looking mode allows very fast observations of these phenomena in many look angles and at variable bandwidths. Fast changes in composition resulting from solar and auroral activity, vertical and horizontal transport can be studied.

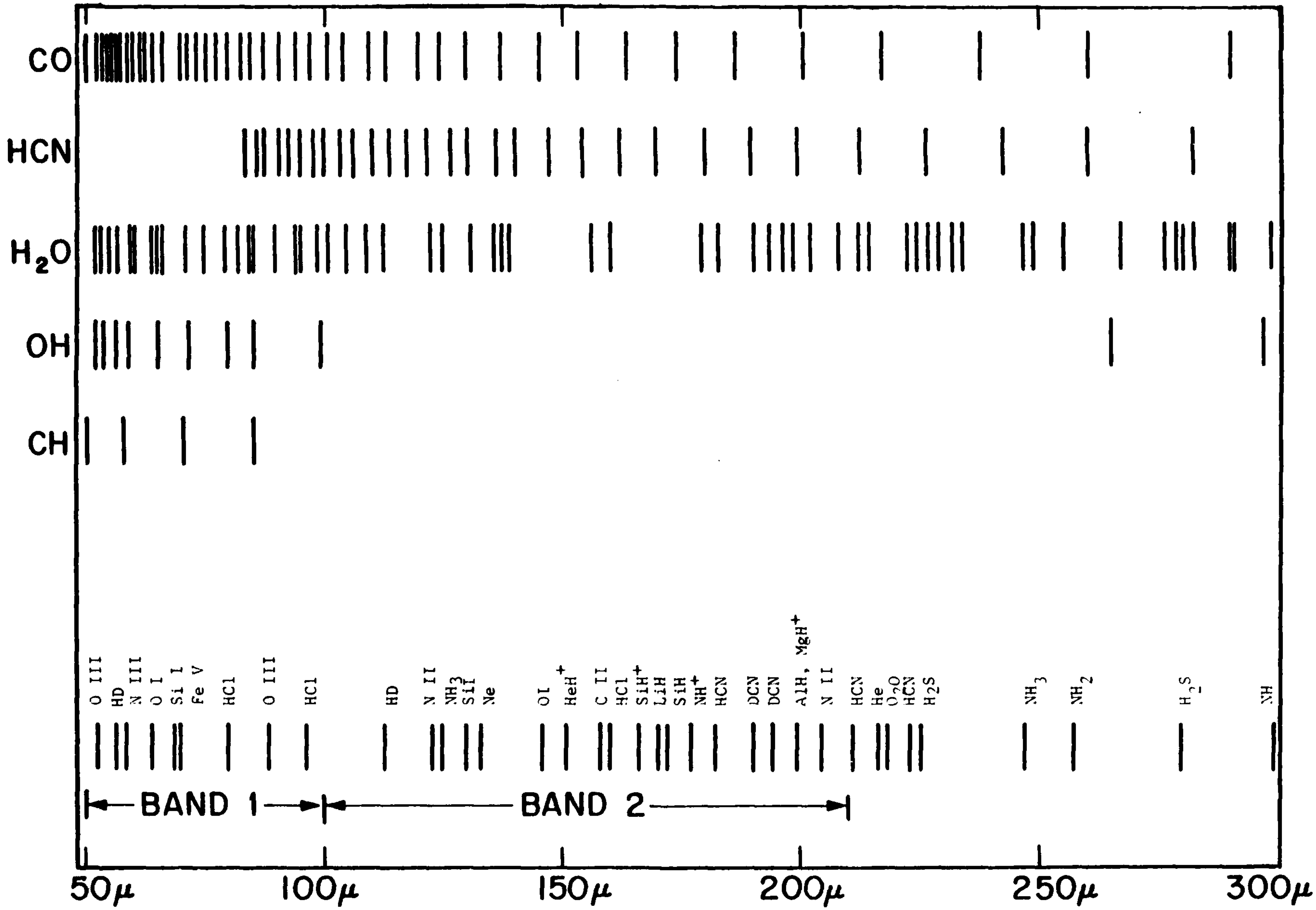
3. Science Objectives

3.1 Overview

FIRIS provides the opportunity for high sensitivity observations at the highest spectral resolution now available in the far infrared. It enables productive studies of the kinematics, composition, and energetics of star-forming regions, and allows fine monitoring of basic diagnostics of the dynamics and evolution of major galactic components. Figure 1.1 illustrates the wide variety of chemical species and ionization states accessible to FIRIS by their far-infrared spectral signatures. Figure 1.2 shows how the excitation of different energy levels for three particular species - [OIII], [OI], and [CII] - converts their fine-structure lines into sensitive probes of local physical conditions.

In the subsections below, we discuss a variety of studies

Fig. 1.1 FAR INFRARED LINES OF THE PRINCIPAL INTERSTELLAR MEDIUM CONSTITUENTS



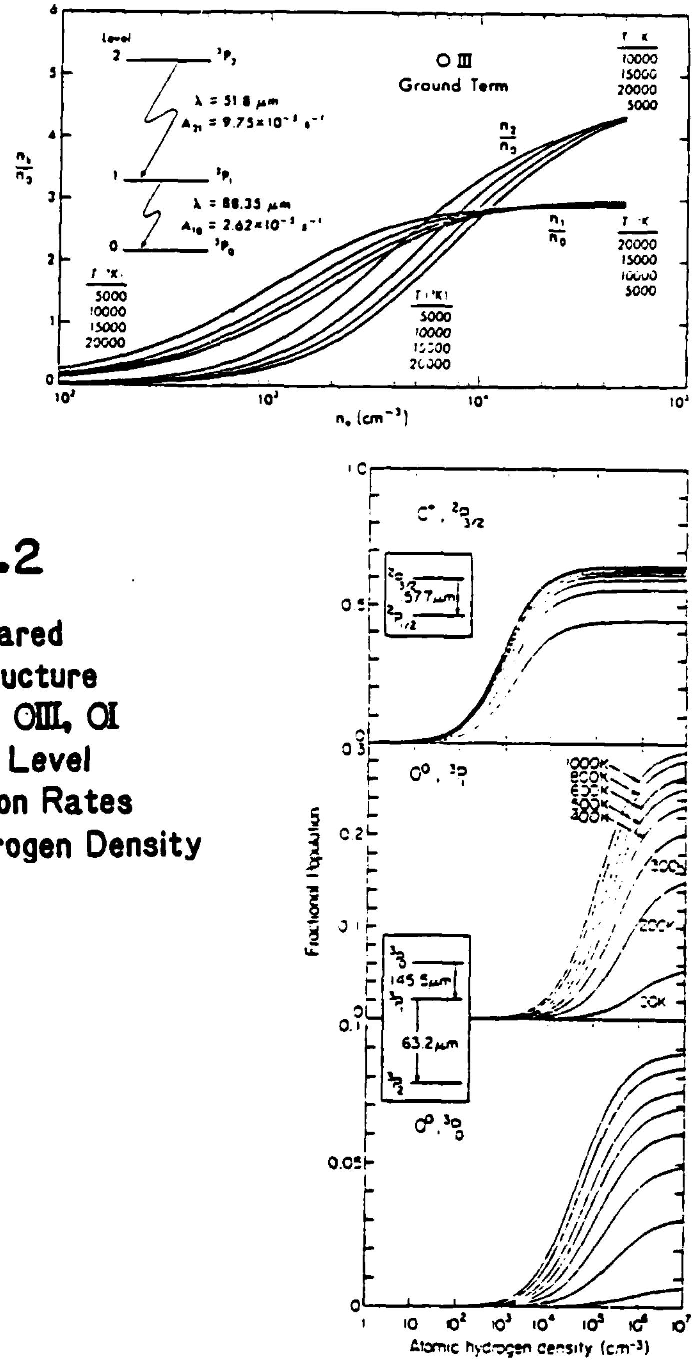


Fig. 1.2

Far-Infrared Fine Structure Lines of OIII, OI and CII: Level Population Rates vs. Hydrogen Density

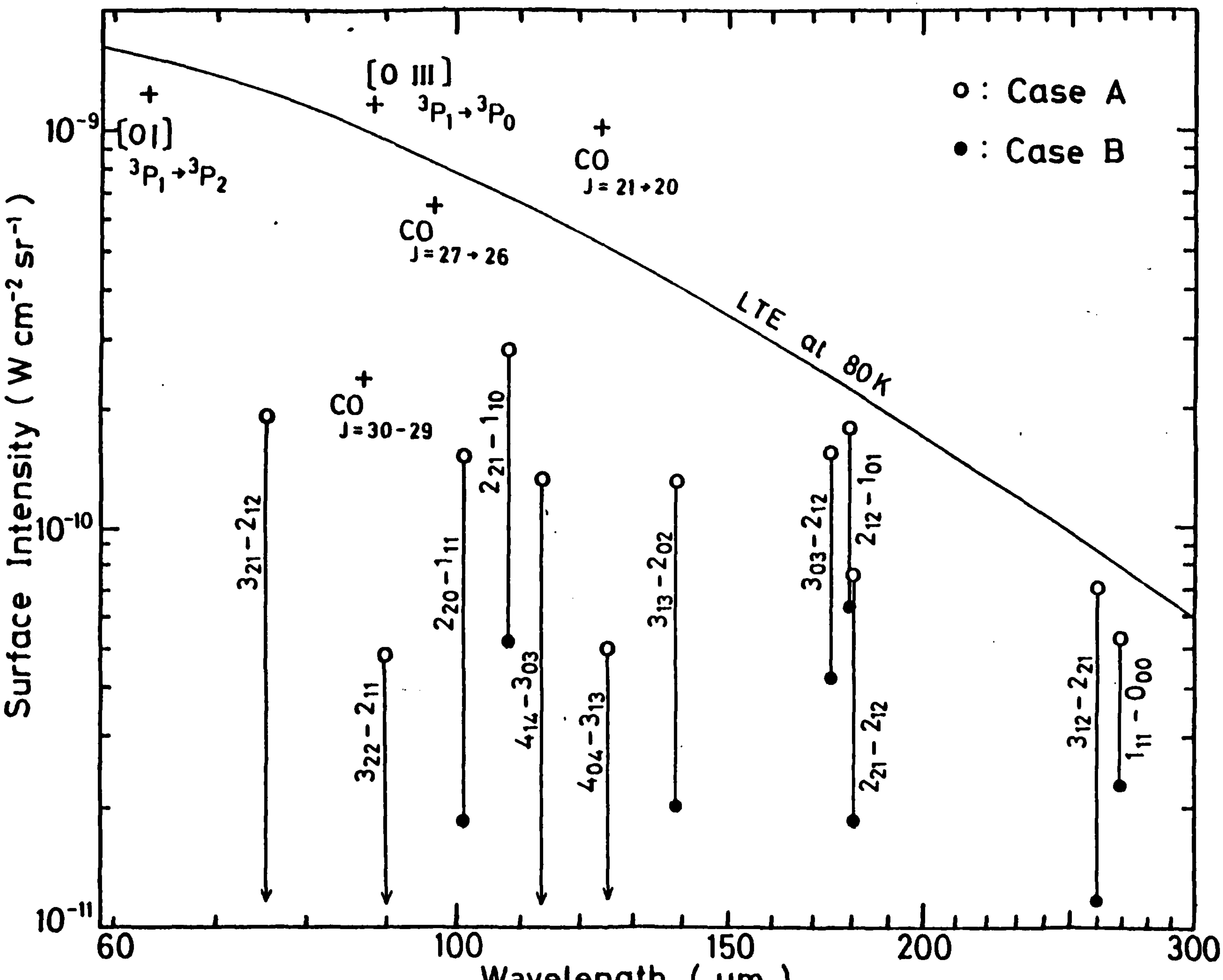
that FIRIS can accomplish on a single shuttle sortie mission, covering a wide range of astrophysical problems.

3.2 Mapping Bright Lines of High Intrinsic Interest

To understand fully the chemistry and large-scale dynamics of young, star-forming regions, it is important to select a small sample of objects typical of their respective classes and conduct the most detailed, spectroscopic studies that are feasible.

Over the years, several sources have been studied that are now regarded as standards. Among HII galactic regions, Orion was given this stature principally because of its high optical surface brightness. NGC 7027 is the standard planetary nebula for the same reason. The advent of molecular studies put M17 into this category and it represents the best edge-on example of a HII region-molecular cloud interface, in contrast to Orion's face-on example. Lastly, L1551 is an example of the molecular flow phenomenon featuring an obscured T Tau star IRS5 (Cohen, Bieging and Schwartz 1983). We will make fairly complete studies of these four sources using the full range of capabilities of FIRIS. This would include complete maps of the ionized nebulae in the major HII region lines—[OIII], [N II], [OI], [CII], [NIII] to establish density and excitation distributions at high spatial and spectral resolutions. We will also measure the long-wavelength H_2O lines (Fig. 2. Shibai and Maihara 1983) and high-J CO transitions from the adjacent molecular clouds, to probe the energetic interaction and the possible stimulation of gravitational condensations within them. The HD emission which should be detectable around the Orion and M17 regions will also

Fig. 2. Estimated line intensities of 12 selected H_2O lines



be mapped to determine total gas masses to compare to CO determined masses. While the neutral gas lines would be observed in HII regions, the mapping of the [C II] and [O I] line in the vicinity of M17 would be emphasized to explore the structural details within the edge-on ionization front. Similarly, searches for the short-wavelength rotational-vibrational lines of CO, NH_3, and C_2H_2 would focus on the known compact sources near the Orion KL region.

3.3 Dynamics of Ionized Gas in Galactic Centers

One of the most exciting prospects of high-resolution far-infrared spectroscopy is the opportunity to probe the dynamics of the obscured nuclear regions of the Galactic center, determining the energy budget of bulk motions and of the local mass distribution (e.g., for compact mass concentrations indicative of black holes). Velocity differences of as much as 200 km s^{-1} have been seen in the HI (Kerr and Valliak 1967; Liszt and Burton 1980) and CO (Scoville 1972) radio line studies, along a line-of-sight toward the Galactic center. Clearly, this region of space is not only the most dynamically complex of any known region in the galaxy but also shows all of the signs of having been a site of considerable star-forming activity within the last few million years. FIRIS will allow us to directly study and map the ionized interstellar medium, not only on a species by species basis but also according to velocity distribution. The high velocity resolution (10 km s^{-1}) and scanning capability ($\pm$ 300 km s^{-1}) of FIRIS will permit the study of the full range of expected gas

motions in the galactic nucleus, allowing us to identify specific clumps of the molecular and ionized medium.

Recent far-IR surveys of the Galactic-Center (Odenwald and Fazio 1984) region within one square degree of the galactic center at 1' resolution reveal nearly 50 discrete sources, most of which are associated with known radio continuum features embedded in the inner 300 pc molecular ring. These sources appear to be giant HII regions ionized by small numbers of O and B-type stars and their general physical properties are not unlike those found in star-forming regions elsewhere in the galactic disk. FIRIS will be the first instrument capable of surveying these far-infrared sources at a velocity resolution ($>10^4$), great enough to distinguish their line emission from that of the extended diffuse background. As most extragalactic far-IR nuclear sources have comparable linear scales, FIRIS will yield the best picture of a fairly widespread phenomenon and allow us to probe the environment of star-forming regions in the nucleus of our galaxy.

3.4 Chemical Evolution of the Milky Way

Optical observations of nearby spiral galaxies show gradients in the abundances of some heavy elements. An important question to answer is whether our own galaxy also shows evidence for such gradients. A survey of a large sample of HII regions in the galactic disc will help us to decide if such a gradient arises from enrichment by planetary nebulae or supernovae or whether it can be explained by mixing with primordial gas, poor in heavy elements, which is preferentially accreted in the outer parts of

the Galactic disk.

The ability of FIRIS to determine element abundances in HII regions will provide us with a unique opportunity to study the chemistry of star-forming regions throughout the galaxy. By selecting only those lines known to be very strong in HII regions, such as [CII] (157.8-microns), [OI] (63 and 145 microns), [OIII] (51.8 and 88.4-microns), [NII] (121.7 and 203.9-microns) and [NIII] (56.3-microns), it will be possible to make abundance estimates for HII regions anywhere within the galaxy in a single pass. One can thus easily trace out the current abundance profile of the Galaxy.

The high resolution of FIRIS permits the isolation of the isotopic variants of the [C II] fine-structure lines in the neutral gas. For optically thin emission, we may expect the [^{13}CII] lines to be 40 to 90 times weaker than the main line. Two 10 minute sessions will be needed to determine intensities in the Orion and M17 regions. This will provide direct measurements of the isotope ratios that can be compared with CO isotope measurements, in order to determine the degree of influence of chemical fractionation on those isotope ratios. Additional observations of molecular clouds with small velocity extents in the galactic center region and in the anticenter will enable isotopic measurements of the chemical evolution gradient of the Galaxy (Searle 1971).

3.5 High Sensitivity Searches

It is a misconception to view FIRIS as only a specific high resolution spectrometer and not as a useful spectral survey

instrument. Although it does not enjoy the "frequency multiplex advantage" of, an FTS, it has a "spatial multiplexing advantage". Its superior intrinsic sensitivity because of background rejection and the high degree of flexibility of the proposed instrument make it superior in overall speed for detecting unexpected weak lines. A prime scientific experiment on the first mission will be a 10 km s^{-1} resolution spectral sweep of Orion KL/BN. The purpose of this experiment is two-fold (1) to generate a complete line assay of this important region and, (2) to perform a census of unidentified features to aid in the interpretation of other scientific experiments.

FIRIS permits a basic experiment on the early stages of galactic evolution, and the identification of primordial galactic material: deep searches for HD, at 112-microns, and HeH^+, at 150 microns. Chemical analysis (Hutchins 1976) shows the likely presence of HD and HeH^+ in primordial gas, and the obvious absence of heavy elements. Although a number of analyses of Galactic chemical evolution have inferred the accretion of substantial amounts of primordial gas onto the Galactic disk, there has been no explicit observational verification. Observations of HI at great distances around galaxies do not distinguish primoridial material from gas stripped by gravitational interactions or enriched by galactic winds.

3.6 Extragalactic [C II], [O I] Observations

There are several galaxies for which immediate observations of the [C II] and [O I] distributions could be very productive. These fine-structure transitions enable one to select out the

neutral gas specifically associated with the star-forming regions. The first galaxies to study would be those with previously demonstrated rich star-forming regions, such as those bright in the 2.6-mm CO line (M51, NGC 6946, Maffei 2, IC 352, M101), and those found to be strong, extended far-IR sources by IRAS (e.g., NGC 2146, NGC 1569, NGC 3690). Also important would be those galaxies whose spiral structures have served as models for optical, radio, and theoretical studies (NGC 3031, NGC 2903).

Substantial time should be devoted to two nearby cases: M31 and the Magellanic clouds. M31 is nearly a square degree in area, and so requires $\sim$ 200 fields. Its closeness does not imply greater brightness as the amount of molecular gas in each arcminute beam is actually less than for most CO galaxies. However, the wealth of data from other investigations (optical, HI, CO, radio continuum, IR continuum, X-ray) and high linear resolution available make it essential to study at least a part of the disk—perhaps the SW complex that is rich in star formation regions. The Magellanic Clouds possess some of the most extreme examples of young stellar population, including the remarkable R136a, a newly-formed, unstable star of $\sim 10^{+3}$ solar masses.

4 LAIRTS Description

4.1 Sensor Characteristics

LAIRTS is a 0.6 x 0.9 m cryogenic telescope designed for STS sortie operation. The sensor consists of the optics, baffles, focal plane instrumentation and the payload consists of the data processing electronics, telemetry package and a dual axis pointing system. Fig. 3 shows an optical layout of LAIRTS and the

OPTICAL LAYOUT OF LAIRTS AND FOCAL PLANE INSTRUMENTATION

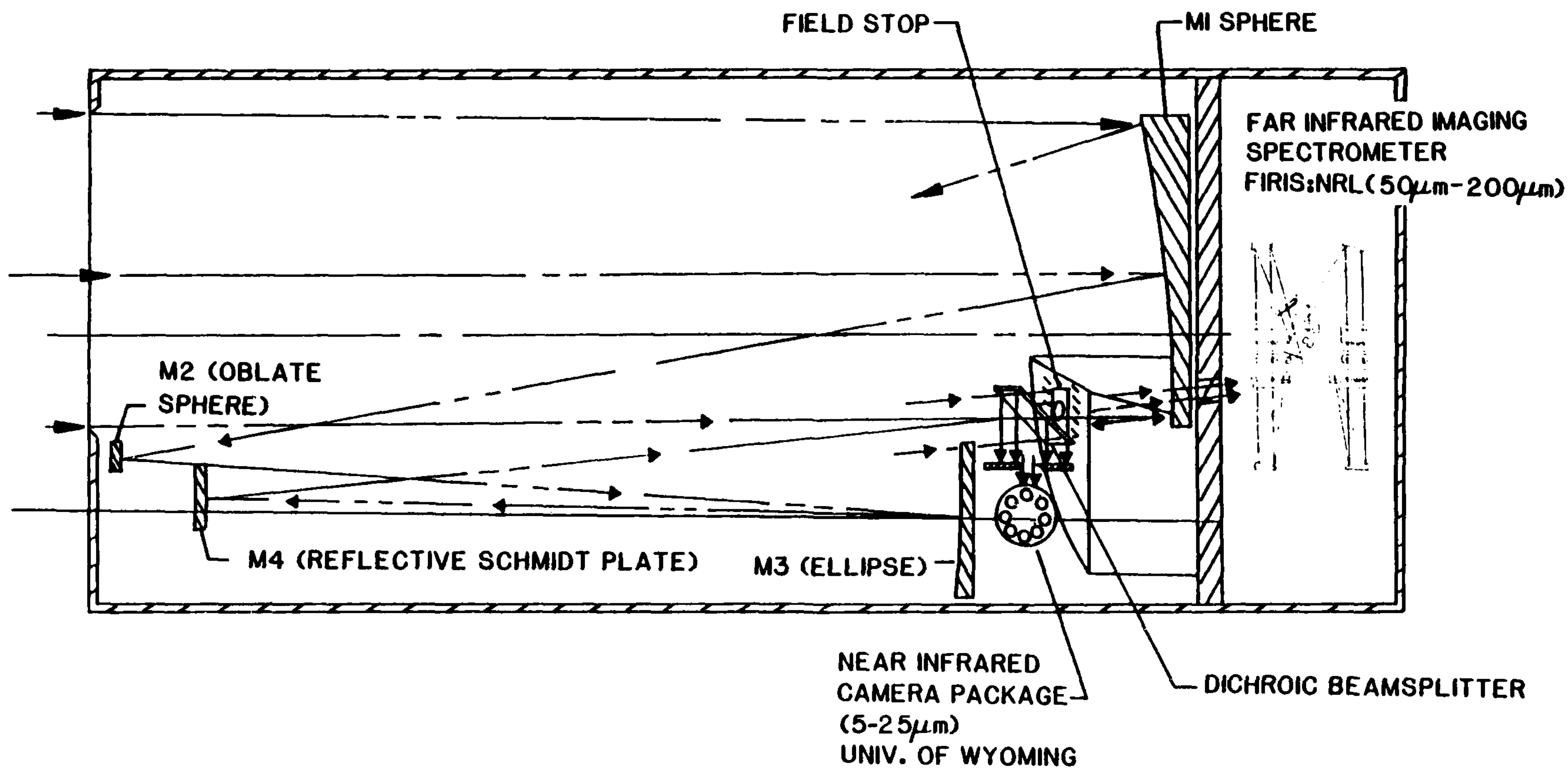


Fig. 3. Optical Layout of LAIRTS and focal plane instrumentation.

proposed focal plane instrumentation. The optics and baffles will be cooled to liquid helium temperatures and heat sinks will be provided at 6 K and 1.75 K for operating the focal plane instrumentation.

A low level CCD television camera will be co-aligned with the sensor and a star tracker using a single bright star will be used to maintain inertial pointings. The pointing goals are to achieve an absolute pointing of 0"5 and to limit jitters to ± 0.25 arc sec and drift to 0.5 arc sec/min for a period of 5 minutes. Fig. 4 shows a conceptual view of the LAIRTS Dual Axis Pointing System which will be gimballed to the ESS pallet on the shuttle. Observing command sequences will be up-linked to LAIRTS using the STS telemetry systems. Data storage will be stored using on board tape recorders.

4.2 Optics

The LAIRTS optical system is an off axis Schmidt spherical primary with an effective collecting area of 3300 cm^2 and a total unvignetted field of view of 1° x 1°. The optical elements as indicated in Fig. 3 are a primary mirror M1, (56 cm x 91 cm), a spherical convex fields lens (M2) for flat field correction, a spherical tertiary mirror (M3) and a Schmidt corrector plate (M4) tilted at 7° to provide an accessible prime focal plane. The source is imaged at M2 and relayed to a flat focal plane tilted from optical axis of M1. The aperture stop is at the primary mirror and imaged on to M4. The system focal length to the final image is 6350 mm with a plate scale factor of 0.54'/mm. The telescope will be diffraction limited at 5 microns with an out of

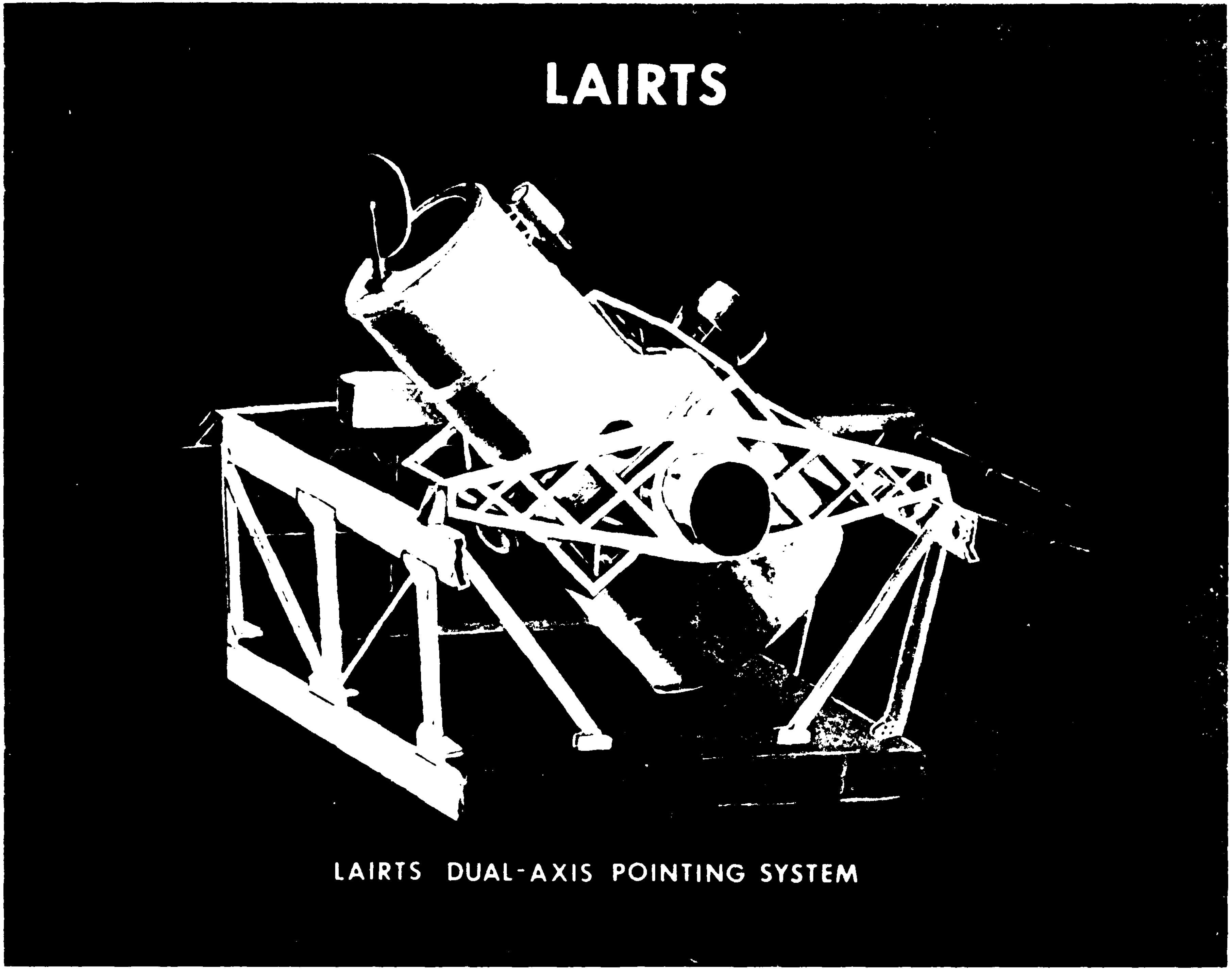


FIGURE 4

field of view rejection of 10^{-13} at 15^{o} off axis.

4.3 Focal Plane Instrumentation

LAIRTS Focal Plane Instrumentation is guided by a set of scientific goals defined by advanced imaging array and spectrometer technology. A staring imaging camera with a 128 x 128 CCD Si:As mosaic array with 5.5 arc sec pixel size is envisaged to operate in the 8-23 micron band with a expected noise equivalent flux density of 10^{-21} w/cm^2 (1 sec integration). This package will be developed by the University of Wyoming to study extended infrared sources associated with HII regions, planetary nebulae and galaxies. The camera system will allow us to achieve complete spatial coverage with better spatial photometric accuracy than has been feasible with multi-channel photometry. The Naval Research Laboratory will provide a high resolution Far Infrared Imaging Spectrometer (FIRIS) using Fabry-Perot techniques in the wavelength interval from about 50 to 200 microns coupled with high sensitivity diffraction limited discrete two dimensional focal plane arrays. The high resolution provides information on the composition, kinematics and physical state of extended man-made and natural infrared sources. Maximum sensitivity is achieved by using the low background environment of LAIRTS which when coupled with the high spectral resolution will eliminate the strong continuum background from warm dusty celestial sources and resolve a variety of atomic molecular lines so as to probe the distribution, and excitation and dynamics of stellar and galactic evolution. The experiment will concentrate on six important groups of lines in the interstellar medium:

[C11] and the hyperfine lines of ^{13}CII at 157 μm; NIII and the hyperfine lines of ^{14}N and ^{15}N; fine and hyperfine structure lines of the strong undetected lines of H_2O, O_2 and their isotopes [100-200 μm]; CO, OH and their isotopes and the HD 56 μm and 112 μm line. FIRIS will have two bands: Band 1, 50 μm to 100 μm and Band 2, 100 μm to 200 μm. Both bands will achieve a typical resolving power of $>10^4$. Each band will be optically matched to an array of detectors to provide spatial information. The Fabry-Perot uses electromagnetic coil displacement drivers with a lead screw drive to obtain parallel motions of up to 6 centimeters, permitting a variable resolving power for flexibility. It uses an optical servo control signal from the etalon plate surfaces to obtain precise setting, parallelism, and scanning. This feature permits microprocessor control for search/scan algorithms (for example, on "empty" spectral fields). The instrument scan and servo design is an extension of that used on a cold, servo-controlled prototype Fabry-Perot being operated by NRL and Aerospace Corporation at the Kitt Peak National Observatory 1.3 meter ground-based telescope. Details of the FIRIS instrumentation will be discussed in the following section.

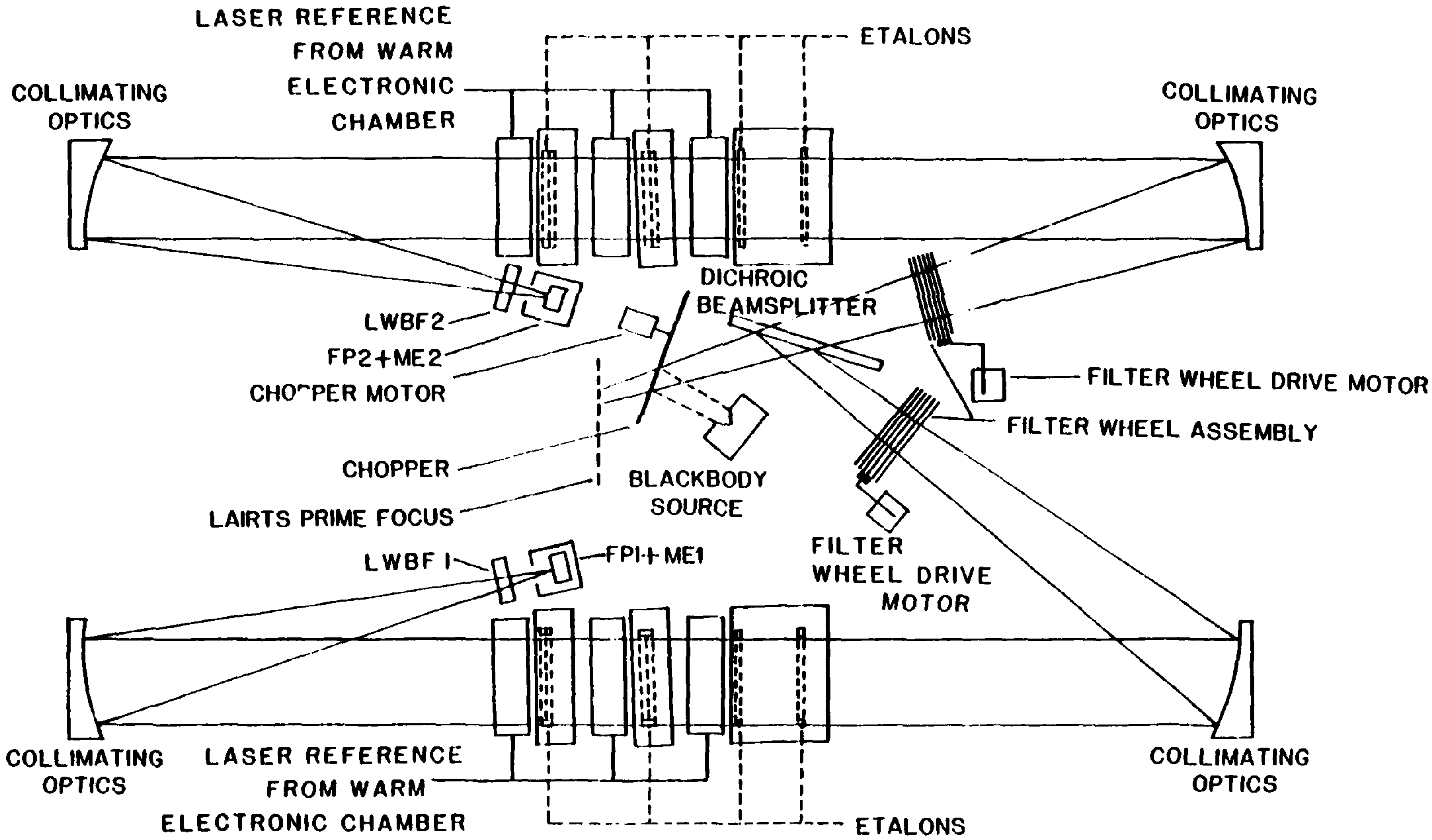
5.0 Far Infrared Imaging Spectrometer Description

5.1. General System Concepts

FIRIS consists of 2 independent Fabry-Perot Imaging Spectrometers which provide nearly continuous wavelength coverage over the range of 50-200 μm, with a maximum resolving power at the center of the field of > 10^4 at all wavelengths. The 10' x 10' FOV is imaged onto 2-D focal plane detector arrays operated near the diffraction limit. The division of the spectral range is divided into bands and is required to be compatible with existing detector and etalon technology. Each band consists of three tandem etalons and an order-sorting filter to block transmission of multiple orders and permit unambiguous frequency measurement. Fig. 5 shows an optical layout of the FIRIS instrumentation proposed for LAIRTS.

The prime focus of the LAIRTS optical image is split into two beams by relay optics. One beam is directed to the near infrared array camera while the other beam is modulated by a chopper and is directed to a beam splitter where it is divided into two bands. A blackbody source is provided for internal photometric calibration of the two bands and a filter wheel assembly consisting of order sorting filters are used to discriminate the various orders of the etalons. The radiation is then collimated, injected through the three etalons, and re-imaged by a parabolic mirror onto a field stop of a focal plane array (FPA). The FPA assembly is made up of photoconductive detectors, plus cryogenic multiplexing readout electronics developed for minimum noise and

OPTICAL LAYOUT OF THE FAR INFRARED IMAGING SPECTROMETER (BANDS 1 & 2)



FPA1+ME1≡FOCAL PLANE ARRAY AND MULTIPLEX ELECTRONICS (BAND 1: 50μm−100μm)
LWBF 1≡LONG WAVELENGTH BLOCKING FILTER
FPA2+ME2≡FOCAL PLANE ARRAY + MULTIPLEX ELECTRONICS (BAND 2: 100μm−200μm)
LWBF2≡LONG WAVELENGTH BLOCKING FILTER

Fig. 5. Optical Layout of the Far Infrared Imaging Spectrometer

maximum sensitivity – properties a Fabry-Perot can utilize because it effectively rejects background/source noise. The analog output is amplified and converted to a digital by a 16-bit A/D converter. The data is added frame-by-frame to integrate each spectral intensity at each field location, and are synchronously demodulated and corrected for glitches from charged particles in the background.

At the end of each source observation the data is transmitted to the Ground Support Equipment (GSE). Other electronic functions provided by the on-board control computer are the redundant master experiment control, servo system control, and housekeeping. A functional block diagram of FIRIS is outlined in Table 1.

TABLE 1

FUNCTIONAL BLOCK DIAGRAM OF FIRIS SPECTROMETER

COMPONENT	FUNCTIONS	BAND 1 (50 μm-100 μm)	BAND 2 (100 μm-200 μm)
Field limiting Aperture	-Stray light control -Limit field to that usable by etalons	-10' x 10'	10' x 10'
Chopper	-Modulate entrance beam at field of view -Modulates blackbody source	-Amplitude: Full field -Frequency: 10 Hz	-Amplitude: Full field -Frequency: 10 Hz
Calibration Source	-Health check	-Blackbody Simulator	-Blackbody Simulator
Filter Wheel/ Filters	-Provide out-of-band blocking	-12 Spectral Filters R = 7 - 20 -Duty Cycle: One setting per 10 Minute Observation	- 12 Spectral Filters R = 7 - 20 - Duty Cycle: One setting per 10 Minute Observation
Collimating Optics	-Collimate field for etalons	-Reflective Optics -Material: Aluminum -Coating: Gold	-Reflective Optics -Material: Aluminum -Coating: Gold
Etalon	-Spectral selection -Spectral isolation -Spectral scanning -Provide spectral resolution	-Three Etalons -Aperture: $\geq$ 8.0 cm -Substrate: Mesh -Coatings: Gold -Scan Range: $\leq$ 50 μm -Etalon Motions:	-Three Etalons -Aperture: $\geq$ 8.0 cm -Substrate: Mesh -Coatings: Gold -Scan Range: $\leq$ 102 μm -Etalon Motions:

		0 to max. Etalon Spacing 0.01,.12,3.0 cm (nominal) -Scan Precision/ Parallelism 10% x resolution element	0 to max. Etalon Spacing .02,.24,6.0 cm (nominal) -Scan Precision/ Parallelism 10% x resolution element
Reimaging Optics	-adjust field size to array size	-Reflective Optics -Coating: Gold aluminum	-Reflective Opti -Coating: Gold aluminum
Detector Array	-Detect incoming photons -Transfer output signal to interface	-13 x 13 array -1.36 x 1.36 mm pixels matched to diffraction limit at 64.5 μm -10'x10' Field Defining aperture -Integrating Cavities -Multiplexed Switched MOSFET -Ge:Ga (discrete) @2.4K	- 7 x 7 array -3.0 x 3.0 mm pixels matched t diffraction limi at 142 μm -10'x10' Field Defining Apertu -Integrating Cavities -Multiplexed Switched MOSFET -Stressed Ge:Ga (discrete) @2.4K or -bolometers (discrete @0.3K)

5.2. Spectrometer Systems

5.2.1 Etalons

To obtain the maximum flexibility in the choice of resolution, operating wavelength, and transmission profile, the spacing of each etalon is adjustable over the full range of its anticipated spacing. In addition, during spectral scanning the parallelism and spacings of the etalons are controlled to a small fraction of the operating wavelength. To achieve these requirements the FIRIS etalon mountings have special characteristics:

1) The movable plate of each etalon is positioned electro-

magnetically via a speaker coil design, with an achievable motion of 2 millimeters. Similar EM drivers have been operated in cryogenic systems and do not suffer from reduced scan capability as do piezoelectric drivers, nor do they require large voltages or currents. The "fixed" plate is positioned with a lead-screw mechanism, with a maximum motion (Band 2) of 6 centimeters.

2) Each etalon has an annular region (around the clear IR aperture) coated to provide visible interference. A visible Laser reference beam from a warm instrument chamber passed through these regions produce fringes sensed by photodiodes on an etalon control card fixed to each etalon. Changes in plate separation are monitored to a fraction of a visible fringe. The optical fringe information generates a servo signal that controls the scan. Three independent drivers and sensors are located around the annular region, permitting the servo to control parallelism during setup and scanning. Absolute spacing calibration is derived from initial optical comparison of the scanning etalons with a stable reference etalon of fixed spacing.

These basic etalon features have several advantageous consequences:

-The lead screw drive mechanism permits a straightforward launch/shipping mode, and a failsafe operation.

-The servo senses the physical, interferometric surface position An analog feedback system is also being considered.

-The available precision of setting (a small fraction of a visible wavelength) is independent of total path separation, and is maintained as an etalon scans over its wide range.

-The sensing mechanism in the cold environment is simple: a fiber optic cable, diodes and an op-amp. The reference light is produced in the warm chamber, which also contains the calibration. The modular design of FIRIS is a particularly important feature. All the etalons use the same driver design, the same reference light, and the same servo control scheme.

5.2.2. Spectral Bands

5.2.2.1. Band 1 (50-100 μm)

Order Sorting Filters: Multimesh interference filters will provide the order-sorting. These filters will have resolving power R_{PF} = 8-20 with passband transmission in the range 60-90%. Such band pass filters can be made between 50-200 μm with $W_g/g \approx$ 5-15%, and T(max) ≃ 60%, with T(rejection) ≃ .1% down to the visible.

Etalons: Band 1 uses free-standing "inductive" wire meshes for its etalon plates. Two basic requirements of a Fabry-Perot etalon are that both its transmission and finesse be as high as possible. The need for high finesse requires that the reflectivity R be high, while the need for high transmission requires that the plate absorptivity A<<(1-R) be low. These requirements at far infrared wavelengths are met by metallic meshes for which A is very low. The most commonly used metal mesh reflectors are the two dimensional "inductive" meshes, which have been widely used as optical elements in far-infrared Fabry-Perot astronomical spectroscopy. (Storey et al. 1979; Belland and Lecullier 1980; and Poulter and Jennings 1983).

The advantages of this type of metal mesh reflectors are (1)

proven success as reflectors in the 50 μm-160 μm spectral region, obtaining finesse values as high as 120 across a 2.5-cm etalon and, with helium-cooled wire meshes, finesse values as high as 200 across a 1 cm etalon; and (2) theoretically understood optical properties when the wavelength is much greater than the grid spacing (Ulrich et al. 1963).

In the ideal case of reflectivity-limited finesse, the finesse goes as λ^2. Thus F=25 at the short wavelength end of the band implies F = 100 at the long wavelength end. Based on our experiences with wire grid mesh etalons, reflectivity limited finesse values $\lesssim$ 100 should be obtainable for the 7.5 cm diameter etalons. The meshes will be mounted using a method in which they are stretched over an optically flat annulus with a bevelled edge. Adhesive is applied to the mesh and the bevelled surface, fastening them together.

An 13 x 13 focal plane array of discrete gallium-doped germanium photoconductive detectors will be used for Band 1. The focal plane arrays will be optimized for a 10' x 10' FOV. Winston light collectors ("heat traps") will be used to focus the radiation from the entrance aperture into the detectors in their integrating cavities while rejecting off axis radiation. Detector and light collector technology have been successfully used in FIRSSE (Far Infrared Sky Survey Experiment) and in far infrared balloon experiments.

A blocking filter will be used in front of the focal plane aperture to reduce stray background radiation. This filter will be a multi-mesh long wavelength pass filter with cut-on

wavelength at 50 μm and transmission of 60%.

5.2.2.2. Band 2 (100-200 μm)

Band 2 has the largest plate motion, 6 cm, in order to get $R \gtrsim 10^4$ at 200 μm. Thus it imposes the weakest constraints on the servo precision, but the strongest on driver motions. Band 2 uses wire mesh prefilters and etalons of a construction similar to that used in Band 1.

The detectors used in the Band 2 will be a 7 x 7 array of stressed Ge:Ga photoconductors or silicon bolometers. Should bolometers turn out to be the devices of choice, their incorporation into the band would entail some additional heat shielding and cooling since they achieve maximum sensitivity at 0.3K. As in Band 1, Winston light collectors will be used to focus the radiation from the entrance aperture to the detectors in their integrating cavities. A multi-mesh long wavelength blocking filter with cut on wavelength at 100 μm will be used in front of the focal plane aperture to reduce stray background radiation.

Both Band 1 & 2 focal plane arrays will be carefully baffled and thermally coupled to the LAIRTS cryogen system for optimum operation.

5.3. Instrument Subsystems

5.3.1. Etalon Driver Subsystem

FIRIS etalons must move slowly over distances up to 6 centimeters for setup at different resolutions, and must scan quickly distances up to 105 μm for acquiring spectra. FIRIS achieves this goal with a two-mode driver.

For slow, large setup motions the "fixed" etalon is moved by a DC torque motor driven lead screw. This drive is supported and translated on two guide posts utilizing linear ball bushings. The bushings maximize rigidity and minimize friction. The metal nut on the lead screw has cross drilled holes (3 opposed at each end) and small Vespel (plastic) rods inserted in the blind holes. The threads are tapped in the Vespel rods. The metal rod holder does not touch the lead screw. The motion of this drive should be smooth enough to allow the servo mechanism to retain lock as it moves.

The scan mode drivers used in taking spectra are electron-magnetic voice coils similar to those now in operation on the cold NRL Fabry-Perot. The scanning etalon is mounted to a fixed housing on three leaf springs, which are compliant over a modest range axially and rigid radially. These coils are able to scan distances of about $\pm$ 1 millimeter, although for taking spectra the usual range of operation will be less than a tenth of this. Three independent coils are used on each etalon, in conjunction with three servo subsystems. The drivers have been tested to temperatures below 77K in observatory conditions (Wollman et al. 1983), and found to meet design specifications. The power consumption and thermal dissipation of the drive systems are below the values for other parts of the instrument, and well below alloted values. The lead screw motor has a $\lesssim$ 1% duty cycle, so is power efficient, and uses a special nut with a low coefficient of friction to minimize heating.

5.3.2. Servo-control Subsystem

FIRIS etalon drivers use a stable optical servo system to control the set up, acquisition of parallel, and scan. A warm electronic chamber (WEC) houses a white light source, a stable visible reference etalon of fixed spacing and a laser. The collimated white light passes through the reference etalon and into the end of the optical fiber bundle. The laser light goes directly into the fiber bundle. One fiber runs to each alignment control position. The light emerging from the fiber is recollimated and injected through an outer annulus of the scanning etalon which has been prepared for visible interference. Photodiodes at each control position sense the light transmitted by the annular portion of the etalon, and feed control signals back to the drivers. The white light and reference etalon allow initial absolute spacing calibration. The laser transmission then monitors changes in spacing and provides the control signal.

This servo system has the advantage that it senses the etalon spacing directly by sensing visible interference in the annular region. Since absolute spacing is established by initial comparison with the stable reference etalon, ongoing calibration is not necessary. From the initial set up position, the servo need only count laser fringes and measure fringe phase, and thus is precise at both small and large separations. The servo design is based on the design of the system in the development instrument presently in operation.

5.3.3. Optical Subsystems

The pre- and post- optics collimate the beam from the

telescope, send it through the etalon chains, and then focus the filtered light onto the array. The parameters of the optical elements will be optimized to produce diffraction limited resolution over most of the FOV seen by the arrays.

Reference Source: White light which is filtered, collimated and passed through an etalon of fixed spacings provides a spacing calibration for all the FIRIS etalons. Because the cold etalons can travel to zero separation this fixed etalon spacing is chosen to be small, thus reducing the collimation precision needed. When the scanning and fixed etalons have the same spacing there is a sharp maximum in the quasi-white light transmitted to the servo photodiodes. The laser mounted in the warm electronics chamber provides accurate interference information at large spacings and must be very well collimated. There is adequate signal-to-noise to do this. Lasers have been successfully operated on spectrometers in space and are suitable for FIRIS.

Fiber Optics: The reference light (laser plus quasi-white light) is transmitted from the WEC to the cold environment via fiber optics, with a cryogenic vacuum connector at the interface similar to what has been tested for the NASA COBE program. Eighteen single mode fibers direct the reference light to the alignment control positions on the edges of the cold etalons where the light is recollimated. The lexan fibers, jacketed with polyethylene, are packaged and routed for minimum heat leakage.

5.3.4. Mechanical Subsystem

Filter Wheel Drive: The filter wheels will be spur gear edge driven to minimize volume. The large rim gear will be aluminum,

to match the structure and mounting bracket material and coefficient for expansion. The pinion gear will be Vespel, to avoid cold welding. The drive motor of choice is a stepper motor. It is not as efficient as a DC torque motor, but the advantage of magnetic detenting and very low (1%) duty cycling outweighs the higher power requirement. By virtue of the gear reduction (8 to 1 or greater) a small (size 15) stepper motor may be used. Backlash in the gear mesh is not critical, since the filter aperture is larger than the light beam.

An enclosed LED/photodiode readout of each filter position is the preferred method for ascertaining filter wheel position. The LED will only be powered on while rotating the filter wheels. Since a maximum of six filter wheels are required, three LED/photodiodes will provide absolute position information.

5.3.5. Electrical Subsystem

Array Electronics: The focal plane electronics will use multiplex electronics operating at cryogenic temperatures. The basic units for the multiplex electronics are the address clocks, readout chip signal amplifiers and correlated double sampler processors.

Array Cabling Electronics: The arrays for each of the two bands will be read out on a pixel basis with the outputs multiplexed by rows and columns. Each detector array will require $\leq$ 25 cables after final multiplexing, for a total of $\leq$ 50 cables which will be tied to the 1.75 K heat sink.

The digital servo controller for each Band will require 50 cables or 100 cables total. In addition, 36 cables are required

to control the various motors while 30 cables are required for housekeeping. The total cable requirements for FIRIS is 216 cables.

5.3.6. Thermal Subsystem

The primary means for achieving and assuring temperature stability will be by annealed copper straps or braid. The straps will be attached to the appropriate coldsink through a rigid end plate which is preloaded with belleville washers on one end, and will run to the detector or component device on the second end . Joint conductance varies significantly with the joint temperature, electrical isolation, and the force applied. The specific temperatures which can be attained on each of the components will vary based on the final design. However, based on the estimated heat loads, differential temperatures across the thermal straps of from 0.2 to 0.5 K should be achievable. This implies a detector temperature of $\approx$2.4K to 3.0 K should be readily achievable.

5.3.7. ON-BOARD DATA PROCESSING SUBSYSTEM

The spectral scans will be controlled automatically by the Master Experiment Control Computer (MECCo) which use a set of stored coordinates to set-up the initial configuration for the etalons at the start of a scan cycle. A second microprocessor, the Data Integrating Computer (DIC), will have the primary responsibility of sampling the array elements, eliminating bad data records due to cosmic ray strikes, differencing the chopped data phase coherently and then co-adding these images for the period of time prescribed by the MECCo. A third set of microprocessors,

the Servo Control Computers (SCCs) are responsible for locking-up the Fabry-Perot in the selected band, maintaining the parallelism of the etalons at a given wavelength and performing the scanning operation. The initial coordinates for each etalon will be provided by the MECCo as will be the scan rate and number of scan steps to be taken.

The arrays contain 218 elements to be monitored at 3 gain steps. The chopping rate is 10 Hz, but the arrays will be imaged 8 times per cycle. In the normal operating mode, post detection processing will be required to compress the sample rate to approximately 1 second intervals. Including the estimated 50 housekeeping words and assuming that 10-bits are allocated per data word, the data rate into the down-link telemetry will be (218 pixels x 3 gains x 10 bits + 50 words x 10 bits) or 7.1 kilobits/sec. In an 8-hour observing session, this amounts to the storage of no more than 7.1 x 8 x 3600 or 204 megabits of data. In the event that the on-board processing fails, the data rate will be 80 times greater or 567 kilobits/sec. To process the data, the DICs will require a memory capacity of about (8, 10 x 10 and 8 5 x 5 images x 64 spectral bins x 3 gain settings) 350 kilobytes including software. If 16-bit data words are used, the normal telemetry rate will be 6.8 kilobits/sec, however, 16-bit encoders are not expected to be available before the start of the LAIRTS program so this number is not reasonable.

Provisions will be made for the likelihood that an instrument malfunction may occur at any time during the flight. The on-board Experiment Control Computer will present to either the

Shuttle Mission Specialist and the ground station a simple, easy to read status indicator which will tell whether the experiment is operating within its designed, or predicted, parameter range. Real-time monitoring of the data itself will be performed by displaying representative spectral scans from each band and spatial images at a spectral point where maximum (or minimum) signal strength is detected.

6. Program Approach

The proposed development of FIRIS and data analysis will be carried out in four phases outlined below. A supplementary study program will be pursued to test a prototype model of the instrumentation using the NASA Kuiper Airborne Observatory and/or the SAO 102 cm Balloon Telescope (or with a proposed 3 meter telescope).

Phase 1. Technology Assessment

A survey of current technology base on Fabry-Perot spectrometers has been completed as part of a proposal of a similar focal plane instrumentation submitted to NASA in response to their announcement for experiments on Shuttle Infrared Telescope Facility (SIRTF). Further detail analysis will be made of existing technology and those which can be applied or adapted to the development of the spectrometer will be identified. Software and hardware requirements for the data acquisition and analysis system will be analyzed for the FIRIS mission.

Phase 2. Spectrometer Design Studies and Laboratory Test

A major part of Phase 2 will be devoted towards the design of the spectrometer with interfaces with AFGL and the LAIRTS sensor contractors. Ray tracing of the spectrometer will be carried out for on and off axis performance of the optical system. FIRIS components and detectors as shown in Table 2 will be evaluated at cryogenic temperatures using test facilities shown in Fig. 6. A prototype spectrometer with a single etalon and discrete detectors will be designed, fabricated and tested at NRL and the technology will be transfered towards the fabrication of the

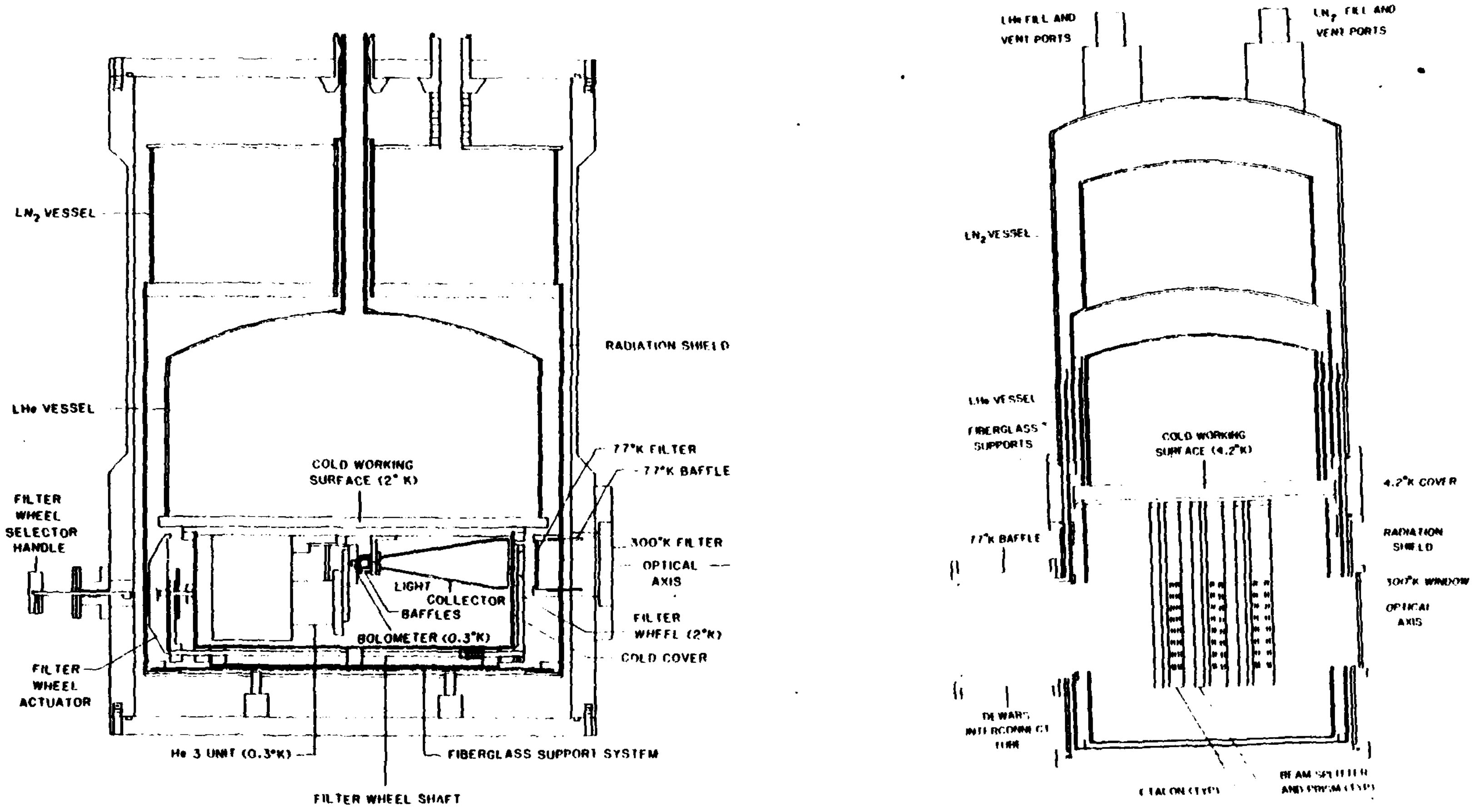


Fig. 6. Test facility to evaluate FIRIS detectors and spectrometer components at cryogenic temperatures

flight unit. A suitable contractor will be identified during this phase for the fabrication of the flight unit.

Phase 3. Fabrication and Test of FIRIS

The spectrometer will be a modular unit so that it can be electrically and mechanically interfaced with the LAIRTS sensor as shown in Fig. 3. FIRIS will be tested for space flight by a selected contractor so as to meet all mechanical thermal, cryogenic and optical requirements. FIRIS will be calibrated at NRL and will be delivered to AFGL for integration with the LAIRTS sensor for final tests. Integration of the sensor to the shuttle will be performed by a selected contractor. NRL will participate in all phases of integration of FIRIS leading to the flight mission. A preliminary program schedule of LAIRTS and FIRIS is presented in Fig. 7.

Phase 4. Data Acquisition and Analysis

This phase consists of all hardware and software development of the data acquisition and analysis systems.

A dedicated, ground-based, computer will use the schedule provided by the observer to compute the etalon initializing coordinates as a function of time. The scheduling and command calculations will be completed well in advance of the actual date of observation so that the command sequences may be optimized using a ground-based model of the FIRIS. A preliminary study of the data will be performed by: analyzing the housekeeping data to determine whether the spectrometer is functioning within expected limits, displaying the full, spatial and spectral data sets for each pointed direction to determine whether further observations

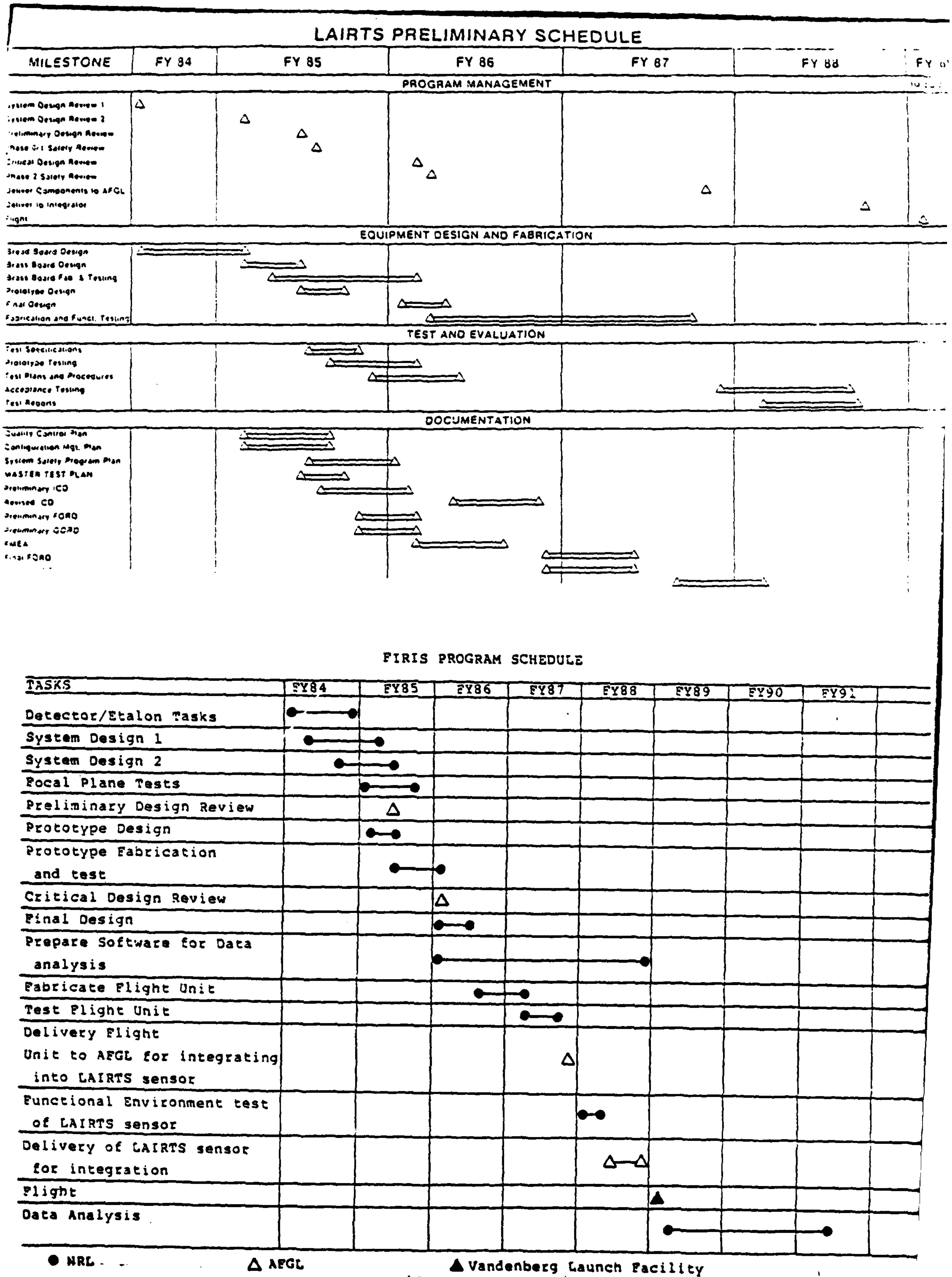


Fig. 7. Preliminary schedule of LAIRTS and FIRIS

may be warranted.

The primary data analysis computer will be located at NRL and will consist of a dedicated, VAX 11/780 with a full compliment of auxilliary input/output (I/O) devices. A library will contain a number of array processing programs, patterned after standard Astronomical Image Processing System (AIPS) software but modified to handle the I/O requirements of FIRIS. There will also be software to perform the aspect calculations so that the pointing information provided by LAIRTS can be combined with the relative position information contained in the array images to render maps in terms of absolute position.

At the anticipated data rates for the arrays (7.1 kbits/sec) and the housekeeping functions we can expect that the direct storage of the anticipated 1100 mega bits of data will entail 1 magnetic tape recorded at 6250 bits per inch during the course of an 8 hour observing program. In the event that the on-board processors fail, the digital outputs from the selected bands will have to be processed in real-time.

Table 2

Laboratory Studies of FIRIS Components

Technical Issues	Participating Organization
1. Optical Design	NRL, SSG, AFGL, AC
2. Detector Studies	NRL, GSFC, AC
3. Cryogenic tests of Spectrometer components	NRL, GSFC, AC
4. Multiplexing Electronics	NRL, BASD, NASA (Ames)
5. Calibration	NRL, NBS, BNL
6. Data Analysis	NRL, AC

AFGL: Air Force Geophysical Laboratory

AC: Aerospace Corporation

BASD: Ball Aerospace Systems Division

BNL: Brookhaven National Laboratory

GSFC: Goddard Space Flight Center

NRL: Naval Research Laboratory

NBS: National Bureau of Standards

NASA: National Aeronautics and Space Administration (Ames Research Center)

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